END

DATE
FILMED

8 - 77

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

ADA041297

RRE

TECHNICAL NOTE

No. 797

RRE-TN-797

CONSIDERATIONS AFFECTING THE CHOICE OF FREQUENCY FOR SURVEILLANCE RADARS

Author: E J Dodsworth

D D C
RECEIVED
JUL 5 1977
A

Royal Radar Establishment,
Procurement Executive,
Ministry of Defence,
Malvern, Worcs.

June 1976

Crown Copyright Reserved

311 750

CONSIDERATIONS AFFECTING THE CHOICE OF FREQUENCY FOR SURVEILLANCE RADARS

E J Dodsworth

RRE TECHNICAL NOTE 797

SUMMARY
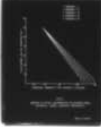
Range performance in the clear, when no clutter or ECM is present, is largely
independent of frequency if the aperture size of the receive aerial is held
constant although there is a small but steady fall in performance as the
frequency is raised because of increasing receiver noise factor and atmospheric
attenuation. If the beamwidth rather than the aperture size is held constant
the performance falls sharply as the frequency increases. The optimum fre-
quency will be that giving the preferred beamwidth with the maximum acceptable
aerial size.

Clutter from the ground, the sea, and from rain is examined and it is shown
that it becomes more severe as the frequency is increased. Clutter from
birds however becomes less severe at higher frequencies.

If constant percentage bandwidth is assumed the range performance in the
presence of noise jamming improves as the frequency is increased. Performance
in chaff can improve as the frequency is increased unless any sort of MTI
processing is involved, when a low frequency is to be preferred.

CONTENTS

1   INTRODUCTION

We are considering here ground-based surveillance radars whose function is
the detection and observation of the movements of aircraft in a large volume
of space. The frequency range with which we are concerned is broadly from
0.2 GHz to 10 GHz.

We consider first various factors which affect the performance in the clear -
that is when the performance is unaffected by clutter, ECM or interference.
Clutter is the generic term for the unwanted echoes from such things as the
ground, vegetation and trees etc, man-made structures on the ground, the sea,
birds, and rain, which may obscure the wanted radar echo from the target
aircraft. ECM (Electronic Counter Measures) includes echoes or signals
received from man-made sources such as a cloud of parasitic reflectors
('Chaff') or jamming, which are deliberately intended to obscure the echoes
from the target aircraft. Interference implies a man-made signal that
accidentally has the same effect. The effect of frequency on the most common
forms of clutter and ECM is considered later.

It should be understood that as we are primarily concerned with the effects
of frequency change all other parameters are to be assumed constant unless
some specific reference is made to them.

2   PERFORMANCE IN THE CLEAR

2.1   The Radar Equation

The range at which a radar can detect an aircraft in the clear, that is with

the performance unaffected by clutter, ECM, or interference of any kind, is fundamentally dependent on the ratio of the total energy received by the radar after reflection from the aircraft during the observation time to the mean thermal noise power per unit bandwidth in the radar receiver. With a radar processing (integrating) n pulses before a decision about the presence or absence of a target is made the observation time - sometimes called the integration time or dwell time - is the interval that elapses between the start of the xth transmitted pulse and the start of the $(x + n)^{th}$ transmitted pulse. In a mechanically scanned radar the observation time is usually the time during which the aerial moves through an angle equal to the one-way half-power beamwidth.

In practice losses inevitably occur and restrict the performance and these can be divided into two broad classes - those that directly affect the quantity of signal energy available at the receiver input terminals and those that result from inefficient processing of the available energy. Losses of the first class often arise merely by definition - for example, if the transmitter output power is measured at the transmitter terminals the losses in the feeder between transmitter and aerial must be allowed for but if the transmitter power is measured at the aerial terminals no such allowance is necessary. The second class of losses arise from departures from the optimum method of signal processing in the receiver and from the fading characteristics of the target echoes, the latter being to some extent dependent on the transmitted waveform.

It may be noted here that if the receiver has the so-called matched filter characteristic appropriate to the transmitted waveform - see for example Skolnik (1) (p 409) - the range performance of the radar in the clear is independent of the actual waveform. The matched filter gives the optimum signal/noise power ratio at the output of the receiver and this is equal to the ratio of signal energy to noise power per unit bandwidth at the input of the receiver.

The ratio of total received energy in the observation time to the mean noise power per unit bandwidth can be written, for a radar in free space, in one of the many possible forms of the radar equation, as:-

$$\frac{E}{N} = \frac{1}{L_A} \cdot \frac{1}{L_B} \cdot \frac{P \cdot T_d \cdot G_T}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} \cdot A \cdot \frac{1}{(NF)(kT_o)} \qquad (1)$$

where E is the total signal energy applied to the receiver input terminals

during the observation time

N   is the effective mean noise power per unit bandwidth at the receiver input terminals.

L_A is a factor accounting for the first class of losses.

L_B is a factor accounting for the second class of losses.

P   is the mean transmitter power.

T_d is the observation time.

G_T is the peak gain of the transmit aerial at the elevation angle of the target aircraft.

R   is the range of the target aircraft.

σ   is the echoing area of the target aircraft.

A   is the effective area of the aperture of the receiver aerial as seen from the target aircraft.

(NF) is the receiver noise factor.

(kT_o) is the product of Boltzman's constant and a noise temperature of $290^\circ K$.

In Eq 1 we have assumed, for simplicity, an aerial noise temperature of $290^\circ K$ and this is discussed in more detail in section 2.3. Some possible misinterpretations of Eq 1 may be avoided if it is remembered that the product $(P.T_d)$ is the total energy output of the transmitter during the observation time.

For the commonly-encountered case of a radar scanning in azimuth at constant speed and covering the same elevation angle on each scan, we have:-

$$T_d = \frac{\theta_A}{\alpha} . D \tag{2}$$

where θ_A is the azimuth half-power beamwidth,

    α is the total azimuth angle scanned (usually $\alpha = 2\Pi$).

    D is the data interval, the time taken to complete one scan.

We can also write:-

$$G_T = \frac{\text{Const.}}{\theta_A . \beta} \tag{3}$$

where β is the total elevation angle covered,

      the constant depends on the illumination taper across the transmit

4

aerial aperture in both planes.

We can select some desired level of performance in terms of the probabilities of detection and false alarm by assigning an appropriate value to $(L_B.E/N)$ and, for this level of performance, we obtain by substituting Eq 2 and Eq 3 in Eq 1 and rearranging:-

$$R^4 \propto \frac{1}{L_A} \cdot \frac{P}{(NF)} \quad A \quad \cdot \frac{D\sigma}{\alpha\beta} \tag{4}$$

Although we assumed a particular method of scanning to arrive at Eq 4, the result is in fact quite independent of the scanning method or sequence if the transmitter energy distribution is the same over the same solid angle.

We can regard the data interval, the target echoing area and the angular dimensions of the scan as design requirements so that the term $\frac{D\sigma}{\alpha\beta}$ is a constant for a particular case, and as the radar designer does not have much scope for reducing losses or improving the receiver noise factor, the only parameters that can be freely chosen to achieve the required performance are the transmitter mean power P and the receive aerial aperture A.

If we regard the aerial aperture as constant the range performance is independent of frequency except for second-order effects such as the variation of receiver noise factor with frequency. However, a fixed-size aperture and a change in frequency implies a change of beamwidth and there are some circumstances in which we might wish to maintain a constant beamwidth rather than a constant aperture size when scaling in frequency. In that case we can say:-

$$A = \frac{\text{Const}}{f^2 \theta_A \theta_E} \tag{5}$$

where f is the radar frequency

θ_E is the half-power beamwidth of the receiver beam in elevation.

Substituting Eq 5 in Eq 4 gives:-

$$R^4 \propto \frac{1}{L_A} \cdot \frac{P}{(NF)} \cdot \frac{1}{f^2 \theta_A \theta_E} \cdot \frac{D\sigma}{\alpha\beta} \tag{6}$$

or $R \propto f^{-\frac{1}{2}}$

So for a constant size aperture the range is independent of frequency but for constant beamwidth it is inversely proportional to the square root of

5

frequency. It is likely that the constant aperture condition will apply
at low radar frequencies where a constant beamwidth would require unaccept-
ably large apertures while the constant beamwidth condition is more likely
to apply at high radar frequencies where the constant aperture condition
could lead to unacceptably narrow beams.

There is an intermediate case in which we choose to keep either the elevation
or azimuth aperture constant and also maintain a constant beamwidth in the
other dimension. For this case:-

$$R \propto f^{-\frac{1}{4}}$$

2.2 Transmitter Power and Receiver Noise Factor

The effect of frequency on the level of transmitter power available to the
radar depends on the assumptions made. For example, if we consider a trans-
mitter valve scaled to operate on some other frequency by multiplying all
the relevant dimensions by the same factor and assume that the limiting
condition is the power per unit area of cooling surface the output power
would be proportional to f^{-2}. However, an examination of manufacturers'
catalogues tends to show that the highest power available from existing
valves is proportional to f^{-1} for frequencies up to 10 GHz or so. This
trend probably reflects the maximum demands that have been made in the past
rather than the intrinsic limitations. On the other hand there may be sit-
uations where it would be more realistic to assume that the raw power avail-
able from the supply mains or generating set is fixed: in such cases the
variation of output power with frequency will reflect the variation of trans-
mitter efficiency and in general efficiency is virtually independent of
frequency over the range we are considering here.

Receiver noise factor does show a steady increase with frequency. Examina-
tion of manufacturers' advertisements for broad-band solid-state low-noise
amplifiers in 1974 showed that the best noise factors offered followed
fairly closely the law:-

$$(NF) = 2 + (0.5 \times 10^{-9})f \text{ dB} \tag{7}$$

Subsequent improvements in technology will certainly result in lower noise
factors than this.

2.3 Aerial Noise Temperature

In Section 2.1 it was assumed for simplicity that the noise power per unit
bandwidth at the receiver input terminals was given by $(NF)(kT_o)$ which is

the case when the aerial noise temperature is 290°K. If however the aerial noise temperature is some other value it is better to work in terms of the system noise temperature at the receiver input terminals. By rearranging expressions quoted by Skolnik (2) (p 2-30) the system noise temperature is given by:-

$$T_s = (NF) T_o - \frac{(T_o - T_a)}{L_r} \qquad (8)$$

where T_a is the aerial noise temperature

L_r is the loss factor of the transmission line between the aerial terminals and the receiver terminals (the noise temperature of this line being assumed to be 290°K).

The noise power per unit bandwidth is then kT_s.

Curves for T_a are given by Skolnik (2) (p 2-32) for a typical case involving arbitrary assumptions about galactic noise, sun noise temperatures, etc but it is also shown that the values given need correction for a neglected component due to ground noise temperature, the correction involving further arbitrary assumptions. The corrected value is:-

$$T_a = \frac{0.876 \, T_a^1 - 254}{L_a} + 290 \qquad (9)$$

where T_a^1 is the aerial noise temperature given by Skolnik's curve

L_a is a loss factor accounting for ohmic loss in the aerial.

Values of aerial noise temperature obtained in this way are given in Table I and plotted in Fig 1, for an elevation angle of 1°. Below a frequency of 500 MHz the aerial noise temperature is virtually independent of elevation angle. At higher frequencies it decreases as the elevation angle increases.

Table I. Aerial Noise Temperature at 1° Elevation Angle

Frequency	Without Ground Correction. T_a	With correction for ground, T_a	
		$L_a = 1.0$ (0dB)	$L_a = 1.26$ (1dB)
GHz	$^\circ$K	$^\circ$K	$^\circ$K
0.2	550	517	471
0.3	240	246	255
0.5	110	132	165
1.0	67	95	135
2.0	63	91	132
3.0	65	93	133
5.0	69	96	136
10.0	86	111	148

The error resulting from the assumption of an aerial noise temperature of 290°K instead of an estimated value as above is not usually very large but it does increase as the noise factor is reduced.

2.4   Aerial Aperture Size

As noted in Section 2.1 above the range performance is independent of frequency if the aerial aperture size is constant but is inversely proportional to the square root of frequency if the beamwidth is held constant. In most situations there is an upper limit to the size of the aerial aperture which is imposed by purely practical considerations. In a static installation with a rotating aerial the maximum aperture dimensions may be as great as 15 to 20 metres without causing difficulty but in a highly mobile radar the acceptable maximum may be no more than about 2.5 metres. Consequently, there will always be some frequency below which the size of the aerial and not a desired beamwidth will be the controlling factor. In one sense this must be the optimum frequency since it combines the desired beamwidth with the maximum size of aerial and so gives the best range performance.

For an illumination taper across the aperture giving reasonably low side-lobes we might take:-

$$\theta_A = 1.2 \frac{\lambda}{l_a} \qquad (10)$$

where λ is the radar wavelength

       l_a is the horizontal dimension of the aperture

then

$$f = \frac{(3.6 \times 10^8)}{\theta_A \cdot l_a} \qquad (11)$$

If we take θ_A = 18 milliradians as a typical figure we can calculate optimum frequencies for various aperture dimensions, as in Table II. The relative range is also tabulated, assuming that both aperture dimensions are scaled proportionately and that all other radar parameters are constant.

Table II. Aperture Size and Frequency for Beamwidth of 18 mrad.

Aperture Dimension	Frequency	Relative Range
m	GHz	
16	1.25	1.00
8	2.5	0.71
4	5.0	0.50
2	10.0	0.35

2.5 Atmospheric Attenuation

One of the losses included in the factor L_A in Eq 1 in Section 2.1 is that due to attenuation resulting from absorption by the oxygen and water vapour in the atmosphere. This loss is greatest at low elevation angles and slowly increases with frequency. The figures in Table III are for an elevation angle of 1° and were calculated for the ICAO standard atmosphere with the addition of a water vapour density of 7 g/m^3 at ground level decreasing exponentially with height; they are taken from curves in Skolnik (2) (p 2-53).

9

Table III. Two-way Atmospheric Attenuation at 1° Elevation

Frequency	Two-way Attenuation	
	Range 100 n-miles	Range 200 n-miles
GHz	dB	dB
0.2	0.3	0.4
0.3	0.5	0.8
0.5	0.9	1.2
1.0	1.4	1.8
2.0	1.7	2.1
3.0	1.8	2.2
5.0	2.0	2.4
10.0	2.7	3.1

2.6 Echoing Area of Aircraft

The figures in Table IV below are echoing area measurements on model air-
craft at scaled frequencies reported by Wilkins and Woolcock (3). In
each case they are mean values over a range of ± 5° in yaw, from head-on,
with the aircraft pitched up at an angle of 3°.

Table IV. Echoing Area of Aircraft

Aircraft	Frequency	Mean Echoing Area		
		Vertical Polarisation	Horizontal Polarisation	Circular Polarisation
	GHz	m^2	m^2	m^2
HS 125	0.63	5.7	7.0	2.2
	1.28	19.9	15.8	11.5
	2.9	7.3	7.5	5.0
Canberra	0.65	13.0	11.4	3.8
	1.32	7.6	14.4	5.5
	3.02	10.0	10:0	8.7

It will be apparent from these figures that no simple general relationship between the echoing area of an aircraft and frequency exists. The best assumption, if no measurements on the particular aircraft of interest are available, is that the echoing area is independent of frequency.

2.7   Reflection from the Earth

The effect of reflections from the earth can be simply demonstrated in principle by considering the model illustrated in Fig 2, in which we assume a flat perfectly reflecting earth with no atmosphere and a radar target at long range so that the direct and reflected rays can be regarded as parallel.

We assume the aerial is used for both transmission and reception and has a polar diagram given by:-

$$A (\theta_c - \theta_e) = \exp \left\{ -\frac{1}{2} \left[\frac{1.665 (\theta_c - \theta_e)}{\theta_E} \right]^2 \right\} \qquad (12)$$

where θ_c is the elevation angle of the beam axis.
The amplitude of the field at the distant target is then:-

$$A (\theta_c - \theta_e) - A (\theta_c + \theta_e) \cos (\frac{4\Pi h}{\lambda} \sin\theta_e) \qquad (13)$$

where h is the height of the radar aerial above the earth's surface.
We have assumed reflection without change of amplitude but with Π phase change.

Fig 3 has been plotted from Eq 13 allowing for two-way tranmission for a particular case.

It will be seen that the effect of increasing the radar frequency - that is, increasing the ratio $\frac{h}{\lambda}$ - is to give more but narrower lobes and in particular to reduce the elevation angle of the first maximum.

In practice the detailed behaviour will be affected by many factors including the earth's curvature, refraction in the atmosphere, the roughness and reflecting properties of the surface, the polarisation of the radar transmission, etc. The subject is discussed by Kerr (4).

The lobing is often ignored at frequencies of 3 GHz and upwards, partly because the surface becomes relatively rougher as the frequency increases and partly because the lobes become very narrow. Nevertheless, there are occasions - such as when observing low-flying aircraft over a calm sea - when they may be significant.

2.8   Anomalous Propagation
Normal refraction in the atmosphere bends radio waves downwards but

meteorological conditions can occur in which the waves have the same radius of curvature as the earth or are even bent back towards the earth's surface. A duct, loosely analogous to a waveguide, is then said to be formed and propagation over many hundreds of miles with little loss can occur in such a duct: this is usually referred to as anomalous propagation.

The lowest frequency that can propagate in such a duct is given by Kerr (4) (p 21) in an expression which can be rearranged to give:-

$$f_{min} = (3.61 \times 10^{11}) \, d^{-3/2} \tag{14}$$

where d is the height of the duct in metres.

This lowest frequency does not represent a sharp cut-off; lower frequencies still may be strongly affected.

Shallow ducts form more easily and more often than deep ones so that anomalous propagation is more likely to be encountered at high frequencies than at low.

Bean et al (5) have produced world-wide charts showing the percentage of the time that trapping of various frequencies can be expected during the four seasons of the year. These charts show a probability of 2% can be expected in parts of the UK at frequencies of 300 MHz and upwards during part of the year.

2.9   Conclusion

With the single exception of reflection from the earth's surface, all the factors we have considered above result in better performance at low frequencies than at high. Changes due to such things as receiver noise factor and atmospheric attenuation, although significant, are small compared to the effect of the aerial aperture size.

Suppose we have a given size of aperture and consider the effect of increasing the frequency from some low value. The signal/noise ratio for a target at fixed range, or the range at which some probability of detection is achieved, will both fall slowly because of noise factor and atmospheric attenuation effects and the beamwidth in both planes will decrease inversely with the frequency increase. Eventually the beamwidth will fall to the minimum acceptable value and this will be at the maximum acceptable frequency. Any further increase of frequency must be accompanied by a reduction in aperture size to maintain constant beamwidth and this results in a rapid loss of performance. This is illustrated in Fig 4 which was based on the noise factor variation of Eq 7, an aerial temperature of 290°K, a target at 100 n miles range and 1° elevation

so that the atmospheric attenuation is given in Table III, the target being situated at the peak of the beam, free space propagation, and all other parameters independent of frequency. Three different aperture sizes are shown in Fig 4 with maximum frequencies of 1.5, 3, and 6 GHz respectively before the minimum beamwidth is reached.

3   PERFORMANCE IN CLUTTER

3.1   Ground Clutter

Ground clutter is the term used to describe unwanted echoes from the ground itself, or from objects on the ground, such as plants or buildings. A feature of ground clutter is that it is always present as it consists of reflection from essentially fixed objects for although the branches of trees, for example, may move in the wind the tree does not change in position. An exception arises with reflections from vehicles moving on the ground which can strictly be regarded as ground clutter but we shall not consider them here.

A commonly accepted model for ground clutter visualises a distributed component and a discrete component. The distributed component is the sum of contributions from many small distributed scatterers, whose mean value varies from place to place with the nature of the terrain (for example, town or country) and its geographical features (a hill may be strongly illuminated by the radar and return a strong clutter signal but a valley behind it will be in shadow and return a weak or no signal). The discrete component consists of echoes from randomly distributed point sources representing such features as aerial masts, farm silos, water towers, specular reflections from suitably sited buildings, etc.

The distributed component can be conveniently characterised in terms of a surface reflectivity which is the echoing area per unit area of surface and is normally designated by σ_o.

Barton (6) gives a relationship between σ_o and wavelength which restated in terms of frequency is:-

$$\sigma_o = (1.067 \times 10^{-12})\, f \qquad m^2/m^2 \tag{15}$$

and this is stated to be a bad case, exceeded over 10% of the surface area at short range in mountainous countryside.

Nathanson (7) (p 264) suggests that σ_o tends to increase with frequency but not faster than linearly with frequency, although figures that he quotes do not indicate any strong systematic variation with frequency.

13

The effective echoing area of distributed clutter per radar resolution cell will be given by:-

$$\sigma_o = R \cdot \theta_A \cdot \frac{c\tau}{2} \sigma_o$$

where c is the velocity of propagation.

τ is the radar pulse length.

If we assume that σ_o is proportional to frequency the effective echoing area of the clutter becomes independent of frequency if the horizontal dimension of the aerial aperture is constant or it increases linearly with frequency if the azimuth beamwidth is constant.

For the discrete component, Barton (6) takes an echoing area of 10^4 m^2, independent of frequency. If the area of the resolution cell is changed, the discrete component changes differently to the distributed component, since it is the probability of a discrete clutter element being included in the cell that will alter and not the echoing area.

The simple model outlined above predicts that a change of size of resolution cell will produce a proportionate change in the echoing area of distributed clutter. However, Warden (8) has shown that in practice the change is considerably greater and consequently a more complex model is needed.

An empirical model that broadly fits experimental measurements at at least some radar sites assumes that the distributed component is not uniformly distributed but concentrated into a number of randomly placed small patches. When the resolution cell is reduced in area (by reducing either the azimuth beamwidth or the pulse length or both) there is then some probability that it will contain no clutter; at the same time σ_o for those cells that do contain clutter must be increased in order to maintain the same average value over the area of the original large cell.

As we are here concerned only with the effects of changing frequency and any resulting change in beamwidth we shall assume that the pulse length is fixed. We shall again assume that the distributed component is proportional to frequency and that the discrete component is independent of frequency.

Suppose that there is a probability p_1 that a surface reflectivity σ_{o1} is exceeded in a resolution cell when the azimuth beamwidth is θ_{A1} and the frequency is f_1. If the beamwidth is changed to θ_{A2} the empirical model gives the probability that the cell will still contain clutter as $p_2 = p \cdot p_1$, where:-

14

$$\log p = 0.3 \log (\theta_{A2}/\theta_{A1}) \tag{16}$$

The surface reflectivity, σ_{02}, in the new cell at a frequency f_2 is then given by:-

$$\sigma_{02} = \sigma_{01} \cdot \frac{1}{p} \cdot \frac{f_2}{f_1} \tag{17}$$

The echoing area of the clutter in the resolution cell will be $\sigma_{c1} \propto \theta_{A1} \cdot \sigma_{01}$ for the original cell and $\sigma_{C2} \propto \theta_{A2} \cdot \sigma_{02}$ for the new cell so that:-

$$\frac{\sigma_{c2}}{\sigma_{c1}} = \frac{\theta_{A2}}{\theta_{A1}} \cdot \frac{\theta_{A2}}{\theta_{A1}} \cdot \frac{\sigma_{02}}{\sigma_{01}} = \frac{1}{p} \cdot \frac{\theta_{A2}}{\theta_{A1}} \cdot \frac{f_2}{f_1}$$

This is conveniently expressed by substituting Eq 16 and taking logarithms:-

$$10 \log (\sigma_{c2}/\sigma_{c1}) = 7 \log (\theta_{A2}/\theta_{A1}) + 10 \log (f_2/f_1) \text{ dB}$$

$$= 10 \log (f_2/f_1) \text{ dB when the beamwidth is constant} \tag{18}$$

$$\text{and} = 3 \log (f_2/f_1) \text{ dB when the azimuth aperture of the aerial is constant.} \tag{19}$$

Warden (8) has shown that ground clutter per resolution cell taken over all ranges can be considered to have a log-normal distribution whose standard deviation is typically 20 dB. The median of the distribution is arbitrary as it depends on the number of cells without clutter that happen to be included. We will assume that the median value is 1.0 m^2 at some frequency f, and also truncate the distribution at a maximum echoing area of + 50 dB relative to 1 m^2.

We assume that the median of the distribution has an echoing area determined solely by the distributed component. Taking the known probability and echoing area of the median at frequency f as a starting point we can calculate from Eq 16 and Eq 18 or Eq 19 the change in probability and echoing area resulting from a change in frequency. We also assume that the maximum echoing area is entirely due to the discrete component so that a change in frequency will not affect the echoing area and will affect the probability only if the beamwidth changes. We thus have two points on the new distribution and can join them with a curve maintaining the log-normal distribution, as in Figs 5 and 6. The resulting estimate of the changed distribution does not pretend to any precision but should indicate trends.

It will be seen that from Fig 5 that an increase of frequency with constant aerial aperture will reduce the ground clutter as the reduction of beamwidth more than offsets the increase in surface reflectivity and the standard deviation falls slowly. Fig 6 shows that an increase in frequency with constant beamwidth increases the median value but reduces the standard deviation. There is no experimental confirmation of these predictions.

As stated above it has been shown that a reduction in the area of the resolution cell can produce a more than proportionate change in the echoing area and the empirical model just described reproduces this effect. However, it is to be expected that the effect will occur over only a limited range of cell area. With cells of large area the probability of encountering no clutter patches may be zero and the echoing area will then be proportional to the area of the cell. With cells having one dimension comparable with the dimensions of a clutter patch a further reduction in that dimension is again likely to result in a proportionate reduction of clutter.

It is known that the echoing area reduction is more than proportional to the area of resolution cell for beamwidths in the range 9 to 30 milliradians and pulse lengths in the range 0.5 to 10 microseconds but it is not known if these values represent real limits to the effect.

3.2   Rain Clutter and Attenuation

The echoing area of a single rain drop when viewed with linear polarisation and at a wavelength large compared with the drop size is given by Battan (9) (p 39) as:-

$$\sigma_c = 0.93 \ . \ \frac{\pi^5}{\lambda^4} \ . \ d^6 \tag{20}$$

where d is the diameter of the drop.

λ is the radar wavelength.

The radar reflectivity of rain is the echoing area per unit volume and depends on the summation of d^6 over all the drops in the volume and this in turn depends on the precipitation rate. A commonly accepted relationship between drop size and rainfall rate is (see Battan (9) (p 89)):-

$$\sum d^6 = 200 \ p^{1.6} \quad mm^6/m^3 \tag{21}$$

where p is the rainfall rate in mm/hour.

Combining Eq 20 and Eq 21, changing units and converting wavelength to frequency leads to the following expression for radar reflectivity:-

$$\eta = (7.05 \times 10^{-48}) . p^{1.6} . f^4 \quad m^2/m^3 \qquad (22)$$

This expression is plotted in Fig 7.

The echoing area of a radar resolution cell filled with rain will be proportional to the product $(\theta_A . \theta_E . \eta)$, other things being equal.

If the frequency is changed but the beamwidths in azimuth and elevation are both held constant the echoing area of the rain will vary as f^4.

If one beamwidth is held constant and the other allowed to vary inversely as the frequency by holding the relevant aperture dimension constant the echoing area of the rain will vary as f^3.

If both aperture dimensions are maintained constant the echoing area of the rain will vary as f^2.

A secondary effect on radar performance arises from attenuation in rain. Nathanson (7) (p 197) has summarised the results of a number of workers and gives a mean curve which is fitted by the equation:-

$$\log A = 1.85 . \log (f \times 10^{-9}) - 3.0 \qquad (23)$$

where A is the two-way attenuation in dB/km/mm/hour of rain.

This attenuation begins to be noticeable at frequencies of 3 GHz and can be quite severe at high frequencies. Table V gives values calculated from Eq 23, for attenuation over a 50 km path in rain falling at a rate of 4mm/hour.

TABLE V   Two-way Attenuation over 50 km in 4mm/hour of Rain

Frequency	Attenuation
GHz	dB
1	0.2
2	0.7
3	1.5
5	3.9
10	14.2

3.3 MTI

The performance of MTI systems can be expressed in various ways, the most generally useful of which is the MTI Improvement Factor which can be defined as the clutter/noise ratio at the input of the MTI canceller divided by the clutter/noise ratio at the output of the canceller. The MTI Improvement Factor is derived by Barton [10] (pp 210 - 219) for single and double cancellation and Skolnik [2] (p 17 - 14) adds the relationship for triple cancellation and the expressions are given in Table VI below. These expressions assume a linear receiver and that the ratio f_c/f_r is small, where f_c is the standard deviation of the clutter spectrum (assumed to be gaussian in shape and to have zero mean) and f_r is the radar prf. In practice a limiting receiver is usually employed to control the false alarm rate in the residue from strong clutter and the Improvement Factor is then degraded. Ward and Shrader [11] have calculated the Improvement Factor with a limiting receiver and the approximate expressions in Table VI are obtained by fitting straight lines to their results.

TABLE VI   MTI Improvement Factor

Cancellation	Improvement Factor with	
	Linear Receiver	Hard-Limited Receiver
Single	$\dfrac{1}{2\pi^2}\left(\dfrac{f_c}{f_r}\right)^2$	$0.011\left(\dfrac{f_c}{f_r}\right)^{-1.75}$
Double	$\dfrac{1}{8\pi^4}\left(\dfrac{f_c}{f_r}\right)^{-4}$	$0.038\left(\dfrac{f_c}{f_r}\right)^{-1.75}$
Triple	$\dfrac{1}{48\pi^6}\left(\dfrac{f_c}{f_r}\right)^{-6}$	$0.051\left(\dfrac{f_c}{f_r}\right)^{-1.75}$

MTI systems operating at constant prf are insensitive to targets moving with velocities which make the doppler frequency equal to a multiple of the prf. These so-called blind speeds occur when the radial velocity is:-

$$v_B = b.\ \frac{c.f_r}{2_f} \tag{24}$$

where $b = 0, 1, 2, \ldots$.

Hence the first blind speed (when $b = 1$) is lower and the spacing between blind speeds is smaller as the radar frequency is increased.

18

The use of staggered pulse intervals (see Skolnik (2) (p 7 - 38) can make the sensitivity much more independent of velocity - except for velocities near zero.

3.4   MTI and Ground Clutter

With ground clutter we will assume that the doppler spectrum due to internal motion of the clutter is negligible compared with the spectrum resulting from the aerial scanning.

If we assume a gaussian beam shape the standard deviation of the scanning spectrum is (Skolnik (2) (p 17 - 9)):-

$$f_c = \frac{0.265}{n} \cdot f_r \tag{25}$$

where n is number of pulse intervals in the time taken to scan through one half-power beamwidth.

For an aerial rotating at constant speed,

$$n = \frac{\theta_A}{2\pi} \cdot D \cdot f_r \tag{26}$$

From Eq 25 and 26,

$$\frac{f_c}{f_r} = \frac{1.67}{\theta_A \cdot D \cdot f_r} \tag{27}$$

The ratio of f_c/f_r is obviously independent of radar frequency if the azimuth beamwidth is constant and is directly proportional to frequency if the horizontal aperture dimension is constant.

It was assumed in Section 3.1 that the strongest returns from ground clutter come from discrete sources and that their echoing area is independent of radar frequency, although the probability of one falling in a resolution cell may be a function of frequency in some circumstances. These strongest returns are most likely to be limited in the receiver and will show the poorest Improvement Factor.

Section 3.3 shows that with hard-limited clutter the Improvement Factor is proportional to $(\frac{f_c}{f_r})^{-1.75}$ for all degrees of cancellation. Hence for the strongest clutter the residue after cancellation will be independent of frequency if the azimuth beamwidth is constant and proportional to $f^{1.75}$ if the horizontal aperture dimension is constant.

19

3.5 MTI and Rain Clutter

Rain clutter differs from ground clutter in many ways but we can particularly note that rain has a mean velocity due to movement with the wind and a much wider doppler spectrum due to turbulence and wind shear - the change of wind speed across the vertical extent of the beam. We assume that the spectrum is wide enough to enable us to ignore the scanning modulation due to aerial motion and that the MTI is adjusted to give optimum cancellation at the mean wind velocity. To obtain a simple formulation for the spectrum we restrict ourselves to the case of a gaussian shape transmit and receive pencil beam completely filled with rain and a linear wind shear with height.

Following Nathanson (7) (pp 205 - 212) with some simplification it can be shown that the standard deviation of the radial velocity of the rain is:-

$$v_{sd} = (1 + 0.09 \ (K.R.\theta_E)^2)^{\frac{1}{2}} \quad m/sec \qquad (28)$$

where K is the vertical wind shear gradient in m/sec/m.

When the wind shear is severe this can be approximated by:-

$$v_{sd} = 0.3 \ (K.R.\theta_E) \qquad (29)$$

The standard deviation of the doppler spectrum is then:-

$$f_c = \frac{2.v_{sd}.f}{C}$$

and

$$\frac{f_c}{f_r} = \frac{(2.00 \times 10^{-9})K.R.\theta_E.f}{f_r} \qquad (30)$$

Hence we have $\dfrac{f_c}{f_r} \propto \theta_E.f.$

From Section 3.2 we have the echoing area of the rain in the resolution cell,

$$\sigma_R \propto \theta_A \cdot \theta_E \cdot f^4$$

From Section 3.3, taking double cancellation as an example, we have the MTI Improvement Factor.

$$I \propto \left(\frac{f_c}{f_r}\right)^{-4} \quad \text{for a linear receiver.}$$

or

$$I \propto \left(\frac{f_c}{f_r}\right)^{-1.75} \quad \text{for a hard-limited receiver.}$$

The cancellation residue $= \dfrac{\sigma_R}{I}$

$\propto \theta_A \cdot \theta_E^5 \cdot f^8$ for a linear receiver

or

$\propto \theta_A \cdot \theta_E^{2.75} \cdot f^{5.75}$ for a hard limiting receiver.

We can now draw up Table VII showing how the cancelled rain residue will depend on frequency in various cases.

TABLE VII   Frequency Dependence of Cancelled Rain Residue (Double Cancellation)

Azimuth Beamwidth	Elevation Beamwidth	Frequency Dependence of Residue with	
		Linear Receiver	Hard-Limited Receiver
Constant	Constant	$\propto f^8$	$\propto f^{5.75}$
$\propto f^{-1}$	Constant	$\propto f^7$	$\propto f^{4.75}$
Constant	$\propto f^{-1}$	$\propto f^3$	$\propto f^3$
$\propto f^{-1}$	$\propto f^{-1}$	$\propto f^2$	$\propto f^2$

For a radar with a fan transmit beam and a pencil receive beam the same frequency dependence will hold but the doppler spectrum will be wider because of the one-way polar diagram of the receive beam. Instead of Eq 28 we have:-

$$v_{sd} = (1 + 0.18 (K.R.\theta_E)^2)^{\frac{1}{2}} \quad \text{m/sec} \tag{31}$$

3.6 Birds

Pollon (12) has shown that at a frequency where the physical size of the bird is small compared with the radar wavelength it will behave as a Rayleigh scatterer and the response will be proportional to f^4. At high frequencies where the wavelength is small compared with the size of the bird the response will vary as f^{-1}. He has further shown that by normalising against the weight of the bird a single characteristic can be obtained for all birds and this is shown in Fig 8. From this the maximum echoing area of a bird is:-

21

$$\sigma_B = (2.92 \times 10^{-4}) . \ W^{\frac{2}{3}} \quad m^2 \tag{32}$$

where W is the weight in grams.

The maximum echoing area occurs at a frequency given by:-

$$f = (5.55 \times 10^9) . \ W^{-\frac{1}{3}} \quad Hz \tag{33}$$

The probability of observing a bird, or a group of birds, with a particular echoing area will naturally depend on the statistics of the bird population in the vicinity of the radar. Pollon has estimated the echoing area probability distribution for birds in Burma and in the USA and has shown that these distributions are quite close to one obtained experimentally by Eastwood and Rider (13) in England. Pollon also shows the effect of radar frequency on the echoing area distribution and Fig 9 is derived from his results. Over the frequency range 1 to 10 GHz the echoing area is roughly proportional to f^{-1}. Fig 10 is derived from Eastwood and Rider's results and shows that the distribution can be approximated by a log-normal curve with standard deviation of 7 dB. Combining the two results enables the median value of the distribution to be estimated to be (66 - 10 log f) dB relative to $1m^2$.

There is no experimental evidence about the effect of size of radar resolution cell (which would be affected if change of frequency affected the beamwidth). Unless the birds were very densely distributed it is more likely to affect the probability of a bird echo occurring in a resolution cell than to change the actual echoing area.

3.7   Sea Clutter

A commonly used model for sea clutter has the clutter power varying as $(Range)^{-3}$ out to some critical range Rc and thereafter varying as $(Range)^{-7}$. Such a model has been derived by Katzin (14) on the basis of a constant surface reflectivity (echoing area per unit of sea surface) and interference between a direct ray and one reflected from the surface of the sea. Katzin gives an expression for the critical range for a target uniformly distributed in height:-

$$R_c = \frac{hH}{0.2\lambda} \tag{34}$$

where h is the height of the radar above the sea

H is the height of the top of the target.

22

Eq 34 can be rewritten in terms of the grazing angle at the critical range:-

$$\sin \phi_c = \frac{\lambda}{5H} \qquad (35)$$

Katzin points out that when this expression is applied to sea clutter the target height H must be much less than the measured wave height.

Skolnik (2) (p 26 - 14) however quotes Eq 35 for sea clutter and puts H as the wave height exceeded by 10% of the waves.

This approach seems to be unsatisfactory because it assumes reflection from a part of the wave whose height above an undefined reflecting surface cannot be easily estimated and in any case there seems little reason why this height should be independent of the grazing angle.

We therefore prefer a purely empirical approach. This is based on values of $10 \log \sigma_o$ (σ_o is the surface relfectivity in m^2/m^2) tabulated by Nathanson (7) (pp 234 to 236) for a wide range of frequencies and grazing angles. Nathanson's figures are a digest of results obtained experimentally by a large number of workers in the field.

An empirical expression which broadly fits Nathanson's figures for all frequencies from 0.5 GHz to 35 GHz for sea states 2 to 5 when the radar is using horizontal polarisation is:-

$$10 \log \sigma_o = -140 + 10 \log f + 15 \log H + 10 \log \left(\frac{X^2}{1+X^2} \right) \quad (36)$$

and when vertical polarisation is used:-

$$10 \log \sigma_o = -38 + 15 \log H + 10 \log \left(\frac{X^2}{1+X^2} \right) \qquad (37)$$

where H is the significant wave height (the average height of the one-third highest waves).

$$X = (1.15 \times 10^{-8}) f \, \phi \, H^{\frac{1}{2}}$$

ϕ is the grazing angle in radians, taking the earth's curvature into account.

Eq 36 is plotted in Fig 11 for three frequencies showing the variation of $10 \log \sigma_o$ with grazing angle and Eq 37 is plotted in Fig 12 for the same frequencies.

The echoing area of sea clutter per resolution cell will be proportional to $(\theta_A \cdot \sigma_o)$. θ_A will change with frequency as usual if a constant aperture

dimension is assumed.

It will be apparent that there is no simple relationship between sea clutter and frequency.

4   PERFORMANCE AGAINST ECM

4.1   Noise Jamming

If we assume a single jammer radiating white noise at a power level such that the received jammer power in the radar receiver is much greater than the thermal noise level, we can derive the appropriate radar equation in a manner similar to that used in Section 2.1 but the performance will now depend on the ratio of total energy received from the target during the observation time to the received jamming noise power per unit bandwidth. We can write:-

$$\frac{E}{J} = \frac{1}{L} \cdot \frac{P \cdot T_d \cdot G_T}{4 \pi R^2} \cdot \frac{\sigma}{4 \pi R^2} \cdot \frac{G_R}{G_{SL}} \cdot \frac{4 \pi R_J^2 \cdot bf}{P_J \cdot G_J \cdot 100} \qquad (38)$$

where L is a factor representing all the appropriate losses.

G_R is the peak gain of the radar receive aerial in the direction of the target.

G_{SL} is the peak gain of the radar receive aerial in the direction of the jammer, G_{SL} and G_R being measured in the same observation period.

R_J is the range of the jammer.

P_J is the mean power of the jammer.

G_J is the gain of the jammer aerial in the direction of the radar.

b is the percentage bandwidth of the jammer.

Eq 38 can be rearranged to give:-

$$\frac{E}{J} = \frac{1}{400\pi} \cdot \frac{1}{L} \cdot \frac{P}{P_J} \cdot \frac{G_T \cdot T_d}{G_J} \cdot \frac{G_R}{G_{SL}} \cdot \frac{R_J^2}{R^4} \cdot \sigma \cdot b.f. \qquad (39)$$

Now, failing any evidence to the contrary, it is reasonable to assume that P/P_J, the ratio of radar transmitter power to jammer transmitter power, is independent of frequency; it can be seen from Eq 2 and Eq 3 that $G_T T_d$ is constant; the jammer aerial gain G_J can also reasonably be assumed to be independent of frequency; and G_R/G_{SL} can be presumed to be constant as long as the beamwidth is unchanged. If the beamwidth does change G_R/G_{SL} can be assumed independent of frequency in the near side-lobe but not in the far side-lobe region, because there the aerial can be taken as having a constant absolute

24

gain on the average while G_R will increase if the beamwidth is reduced.

However, if we ignore this rather special case and any change of losses or target echoing area with frequency we can deduce from Eq 39 that at a constant level of performance in terms of target detection:-

$$R \propto f^{\frac{1}{4}}$$

and consequently that a high radar frequency is desirable to combat noise jamming.

In the above we have assumed that the radar target and the jamming source are separated in space but there may be occasions when the radar target is itself the jamming source. In this case $R = R_J$ and we have:-

$$R \propto f^{\frac{1}{2}}$$

for the so-called self-screening target.

The use of a narrow radar receive beam minimises the solid angle in which the jammer is most effective and this would be a further reason for choosing a high frequency if the aerial aperture dimensions are fixed.

4.2   Chaff

The most useful basis for assessing the effect of frequency on chaff is probably to consider the echoing area per unit weight of fully dispersed chaff. The echoing area of a radar resolution cell can then be assumed to be the product of the number of dipoles in the cell and the average echoing area per dipole.

The average echoing area per dipole when cut to the optimum length is quoted by Nathanson (7) (p 223) as $0.18\lambda^2$. The optimum length is itself proportional to λ and so inversely proportional to frequency.

If we assume that the dipoles are cut from material of the same width and thickness the number per unit weight will be proportional to frequency and the echoing area per unit weight inversely proportional to frequency. However, if the width and thickness of the material are both inversely proportional to frequency (or the diameter is inversely proportional to frequency if the material is in filamentary form) the echoing area per unit weight will also be proportional to frequency.

As a general assumption it is probably reasonable to assume a situation between
these extremes and take the echoing area per unit weight as being independent
of frequency. This assumption will also cover the case of chaff bundles con-
taining mixed lengths which can be chosen to provide substantially constant
echoing area over several octaves.

When the chaff is dispersed at constant density - constant weight per unit
volume - the echoing area per resolution cell with a pencil beam filled with
chaff will be proportional to $(\theta_A \cdot \theta_E)$. This will be independent of frequency
if both beamwidths are constant, proportional to f^{-1} if one of the aperture
dimensions is constant, and proportional to f^{-2} if both aperture dimensions
are constant. If the chaff is in a thin layer so that the vertical extent
of the beam is not filled, the echoing area will to a first approximation
depend on the azimuth beamwidth only and will be proportional to f^{-1} if the
horizontal aperture dimension is constant.

If MTI is used against chaff, the performance will depend on the echoing area
of the chaff and on its doppler spectrum which can be estimated in the same
way as that of rain in Section 3.5. If we again assume a thin layer of chaff
Eq 30 needs modification with the thickness of the chaff layer replacing the
vertical extent of the beam $R\theta_E$, and the width of the doppler spectrum is then
proportional to f. The MTI Improvement Factor with a linear receiver will be
proportional to f^{-2}, f^{-4}, or f^{-6}, depending on whether single, double or
triple cancellation is considered. As the frequency increases the deteriora-
tion of Improvement Factor more than offsets the reduced echoing area obtained
with constant aperture size.

Consequently, for a radar without MTI a high frequency is to be preferred for
working in chaff if this enables the beamwidth to be reduced, but if MTI is
used a low frequency is desirable.

5   CONCLUSIONS

For a radar operating the clear, with no clutter or ECM, the range performance
is not a rapid function of frequency as long as the size of the aerial aperture
is maintained constant as it is affected only by the increasing receiver noise

factor and the increasing atmospheric attenuation as the frequency is raised
and by the more complicated variation of aerial noise temperature. However,
with a constant aerial aperture the beamwidth will decrease as the frequency
increases.

In practice there will be some maximum acceptable size of aerial dictated by mechanical or operational considerations and there will be some maximum acceptable beamwidth determined by considerations of angular accuracy or resolution. The optimum frequency will then be that which gives the maximum acceptable beamwidth with the maximum acceptable aerial size. At frequencies lower than this optimum the beamwidth will be too great and at higher frequencies the range performance will be reduced.

One reason for preferring a higher to a lower frequency is that this makes reflections from the ground less serious and puts the first interference lobe at a lower elevation angle.

The effect of frequency on ground clutter is not well established but it is believed that the strongest clutter echoes are likely to be from discrete objects and that the echoing area of these can be regarded as independent of frequency. If change of frequency results in change of size of resolution cell it is the probability of finding one of these discrete echoes in the cell that changes and not the maximum echoing area. If hard-limited MTI is used to remove ground clutter the cancelled residue is proportional to $f^{1.75}$ with a constant horizontal aperture dimension and is independent of frequency if the azimuth beamwidth is constant.

The effect of frequency is much more marked with rain clutter than with ground clutter and the performance falls rapidly as the frequency is raised.

With sea clutter the effect of frequency is more complicated but in most circumstances the clutter increases as the frequency increases.

The echoes from birds tend to be reduced as frequency increases.

With systems having a constant percentage bandwidth the range in the presence of noise jamming increases as the frequency is raised.

In the presence of chaff a low frequency is to be preferred when some form of MTI processing is involved.

To summarise:- by operating at a high frequency we can obtain better range in the presence of noise jamming, less clutter from birds, and an acceptable beamwidth from a small aerial, but the range performance in the clear will be reduced because of the small aerial and the radar will be more susceptible to ground clutter, rain clutter, sea clutter and chaff than one at lower frequency.

27

REFERENCES

1   Skolnik M,   Introduction to Radar Systems, McGraw-Hill 1962.

2   Skolnik M, Ed.   Radar Handbook, McGraw-Hill 1970.

3   Wilkins L E and Woolcock S C,   Determination of Radar Echoing Areas
     of Canberra and HS 125 Executive Aircraft, unpublished work by
     EMI Electronics Ltd under MOD Contract, 1973.

4   Kerr D E, Ed.   Propagation of Short Radio Waves, MTI Radiation
     Laboratory Series, Vol 13, McGraw-Hill, 1951.

5   Bean B R et al   A World Atlas of Atmospheric Radio Refractivity,
     ESSA Monograph No 1, 1966.   (Environmental Science Services Administration
     US Dept of Commerce).

6   Barton, D K   Radar Equations for Jamming and Clutter, Supplement
     to IEEE Trans Vol AES-3 p 340, Nov 1967.

7   Nathanson F E   Radar Design Principles, McGraw-Hill, 1969.

8   Warden M P   An Experimental Study of some Clutter Characteristics.
     Agard Conference Proceedings No 66 - Advanced Radar Systems - Istanbul,
     1970.

9   Battan L J   Radar Observation of the Atmosphere, University of Chicago
     Press, 1973.

10   Barton D K   Radar Systems Analysis, Prentice-Hall, 1964.

11   Ward H R and Shrader W W   MTI Performance Limitation caused by Limiting,
     IEEE Eascon Record p 168, 1968.

12   Pollon G E,   Distribution of Radar Angels, IEEE Trans Vol AES-8,
     p 721, 1972.

13   Eastwood E and Rider G C,   Grouping of Nocturnal Migrants, Nature
     Vol 211 p 1143, 1966.

14   Katzin M,   On the Mechanisms of Radar Sea Clutter, Proc IRE Vol 45,
     p 44, 1957.

1. T_a' WITHOUT GROUND CORRECTION
2. T_a WITH GROUND CORRECTION. AERIAL OHMIC LOSS O.
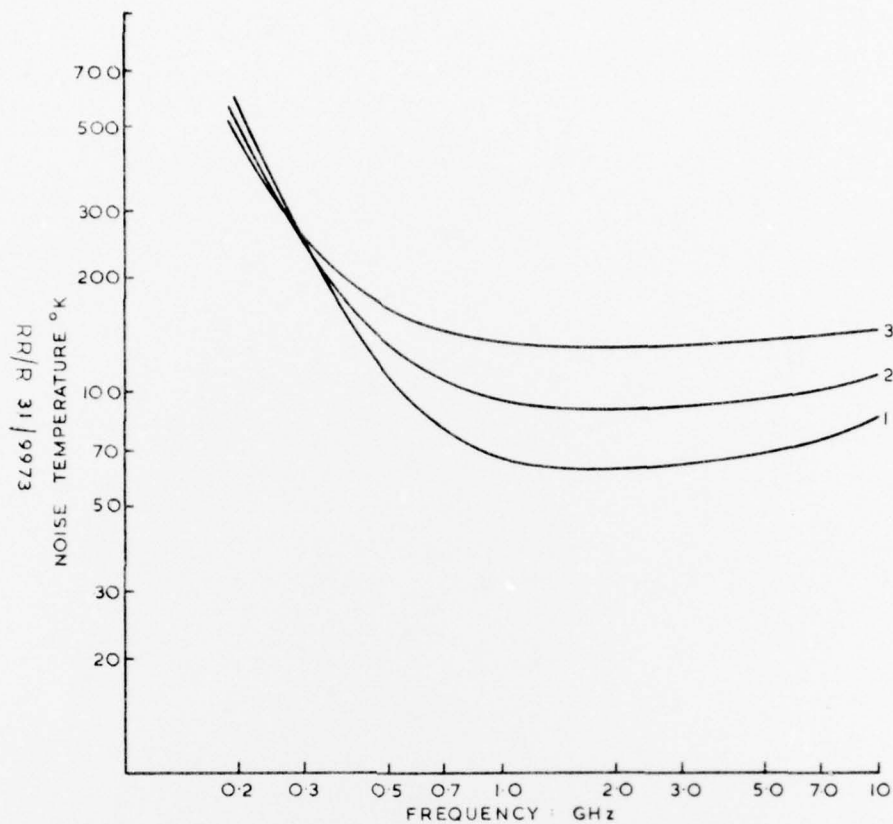3. T_a WITH GROUND CORRECTION. AERIAL OHMIC LOSS 1·0dB

FIG. 1.

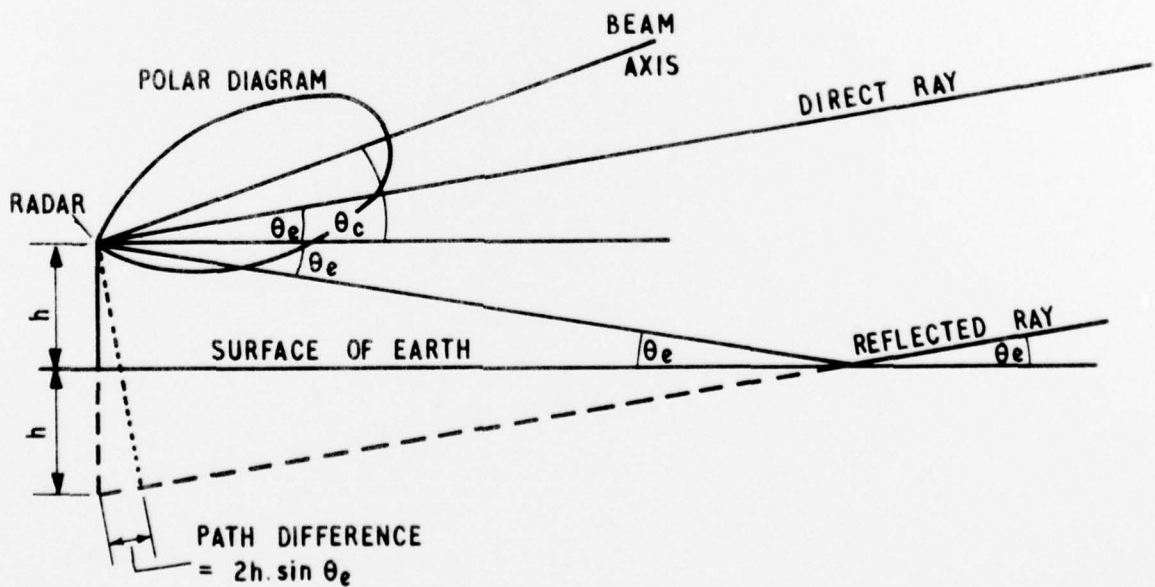AERIAL NOISE TEMPERATURE AT 1° ELEVATION ANGLE.

FIG. 2.

REFLECTION FROM SURFACE OF THE EARTH.
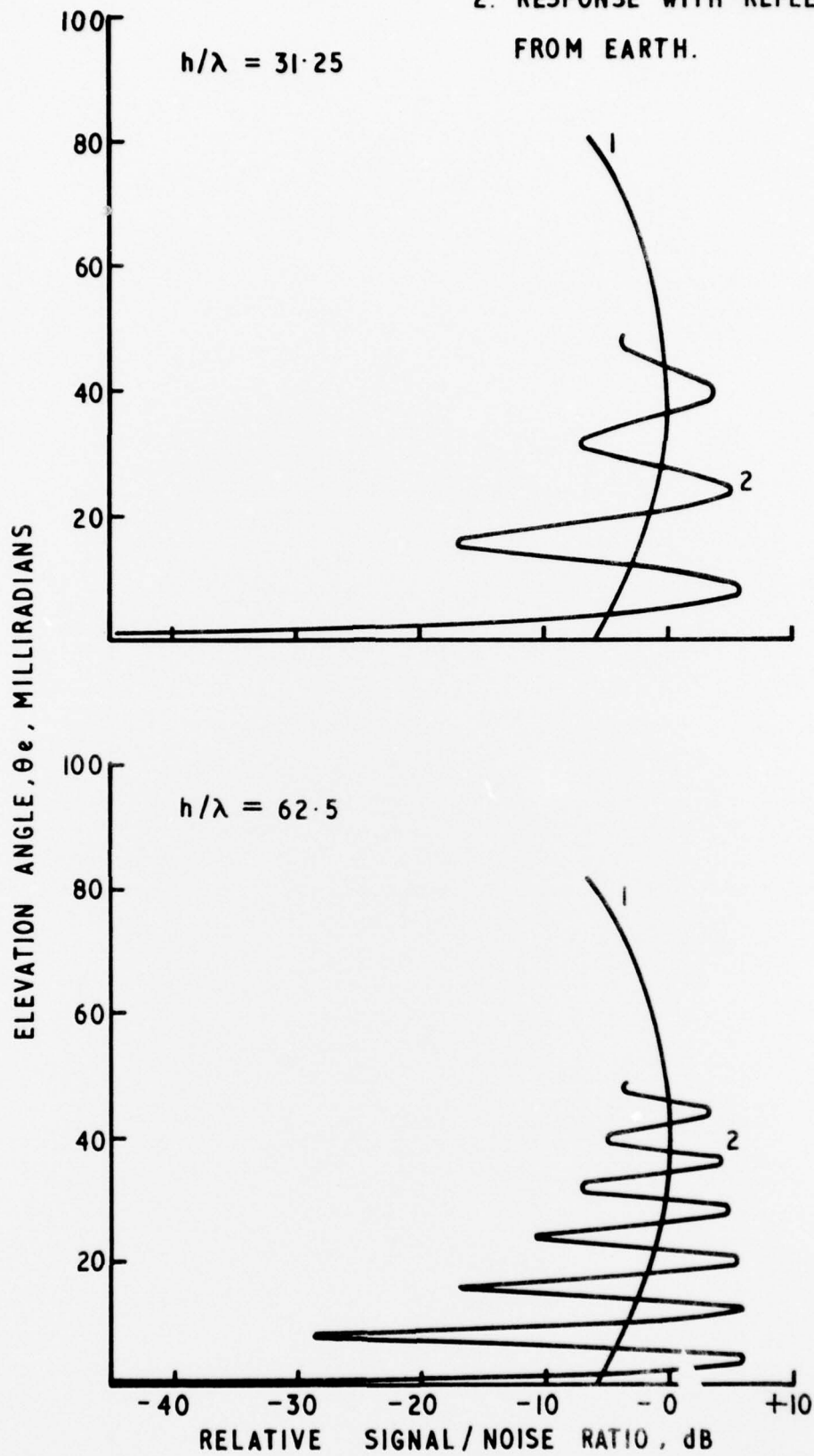
FIG. 3.

EFFECT OF REFLECTION FROM EARTH'S SURFACE.

RR/R 3/19965

FIG. 4

PERFORMANCE IN THE CLEAR.

1. CONSTANT APERTURE AREA A
2. CONSTANT APERTURE AREA 4A
3 CONSTANT APERTURE AREA A/4
4 CONSTANT BEAMWIDTH

FREQUENCY, GHz

RELATIVE SIGNAL/NOISE RATIO, dB
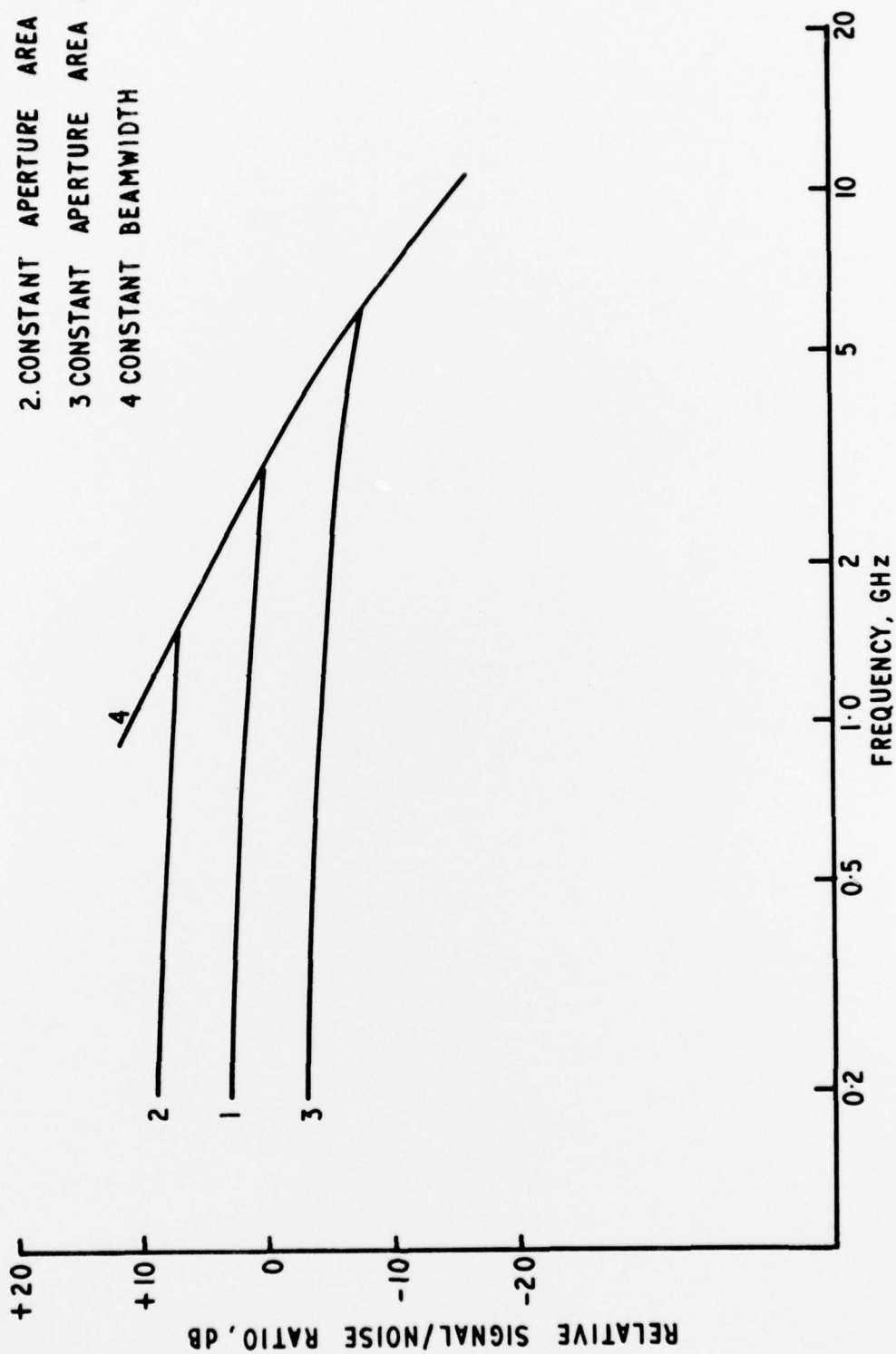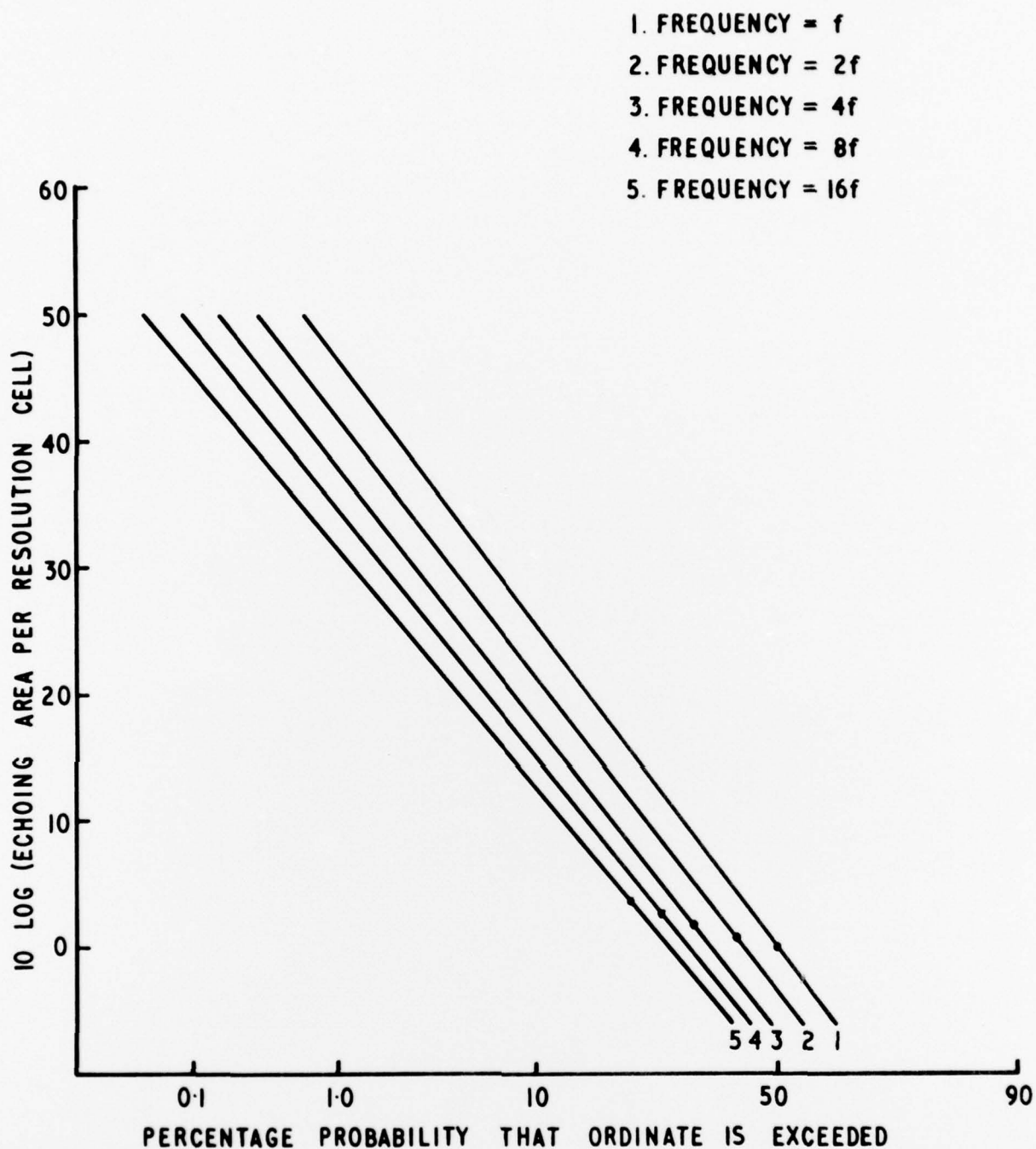
FIG. 5

GROUND CLUTTER; DISTRIBUTION OF ECHOING AREA.

EMPIRICAL MODEL. CONSTANT APERTURE SIZE.

RR/R 3/19967

1. FREQUENCY = f
2. FREQUENCY = 2f
3. FREQUENCY = 4f
4. FREQUENCY = 8f
5. FREQUENCY = 16f
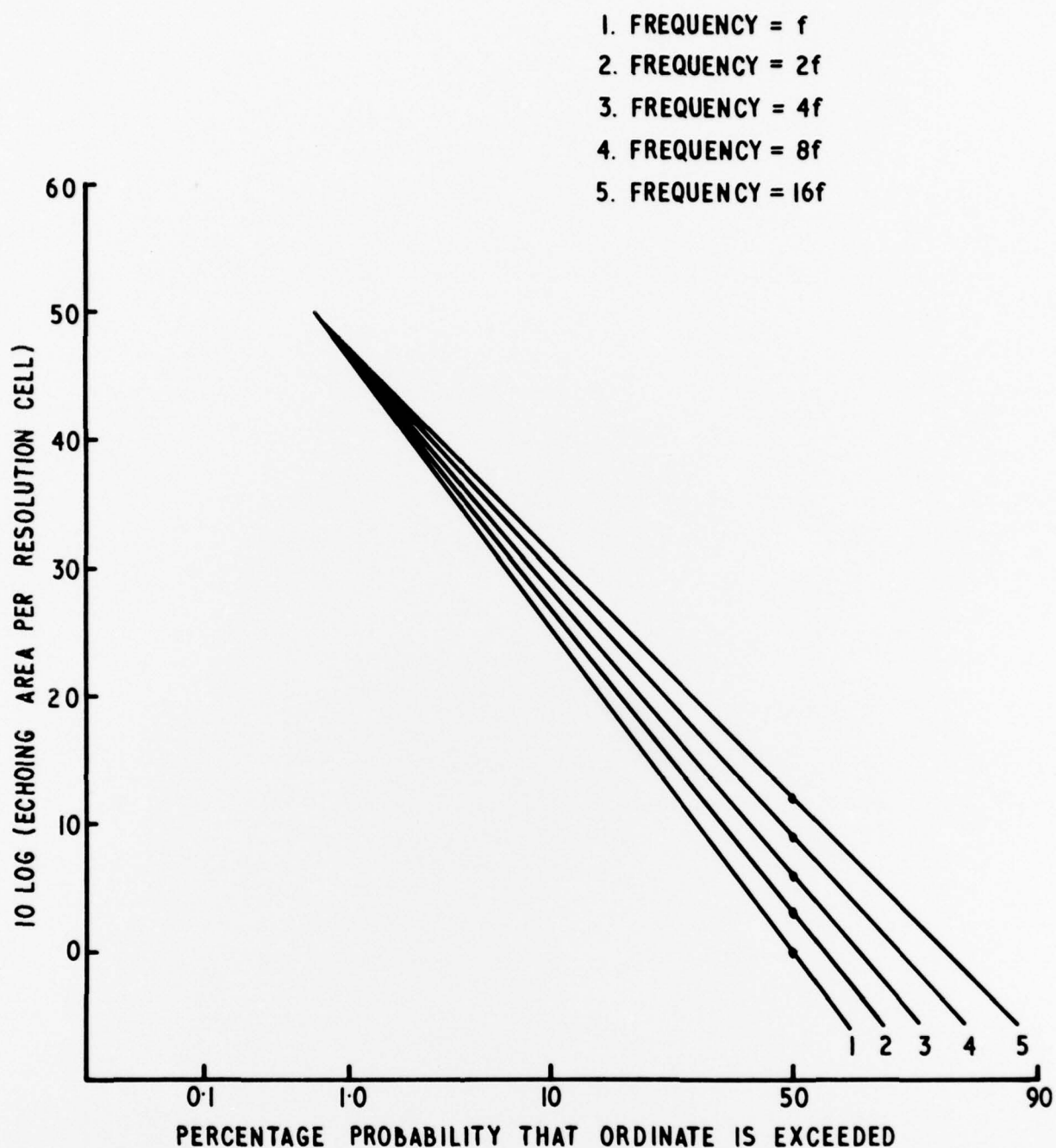
FIG. 6.

GROUND CLUTTER ; DISTRIBUTION OF ECHOING AREA.
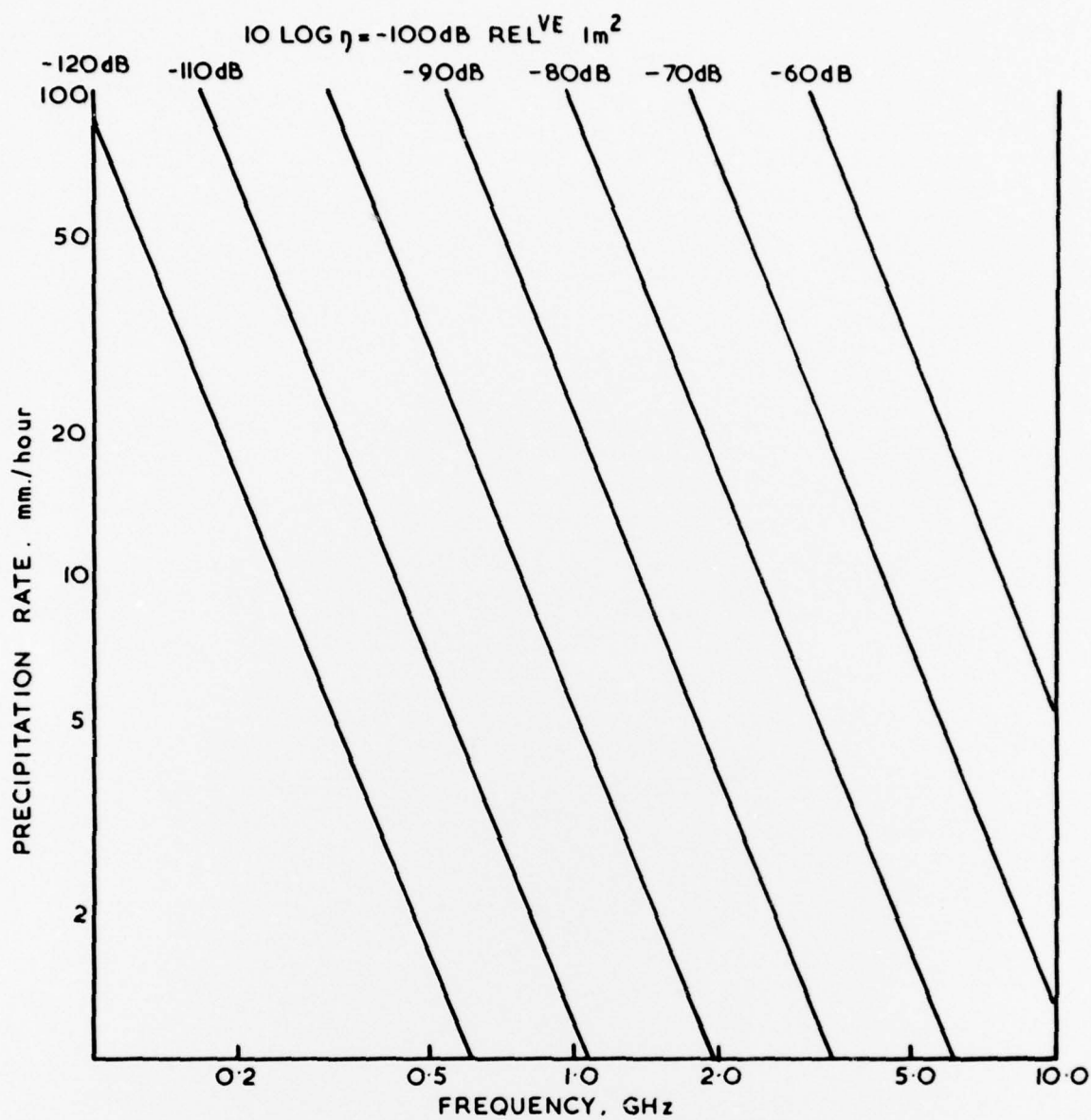
EMPIRICAL MODEL. CONSTANT BEAMWIDTH.

FIG. 7.

REFLECTIVITY OF RAIN ,η ,AS FUNCTION OF FREQUENCY AND PRECIPITATION
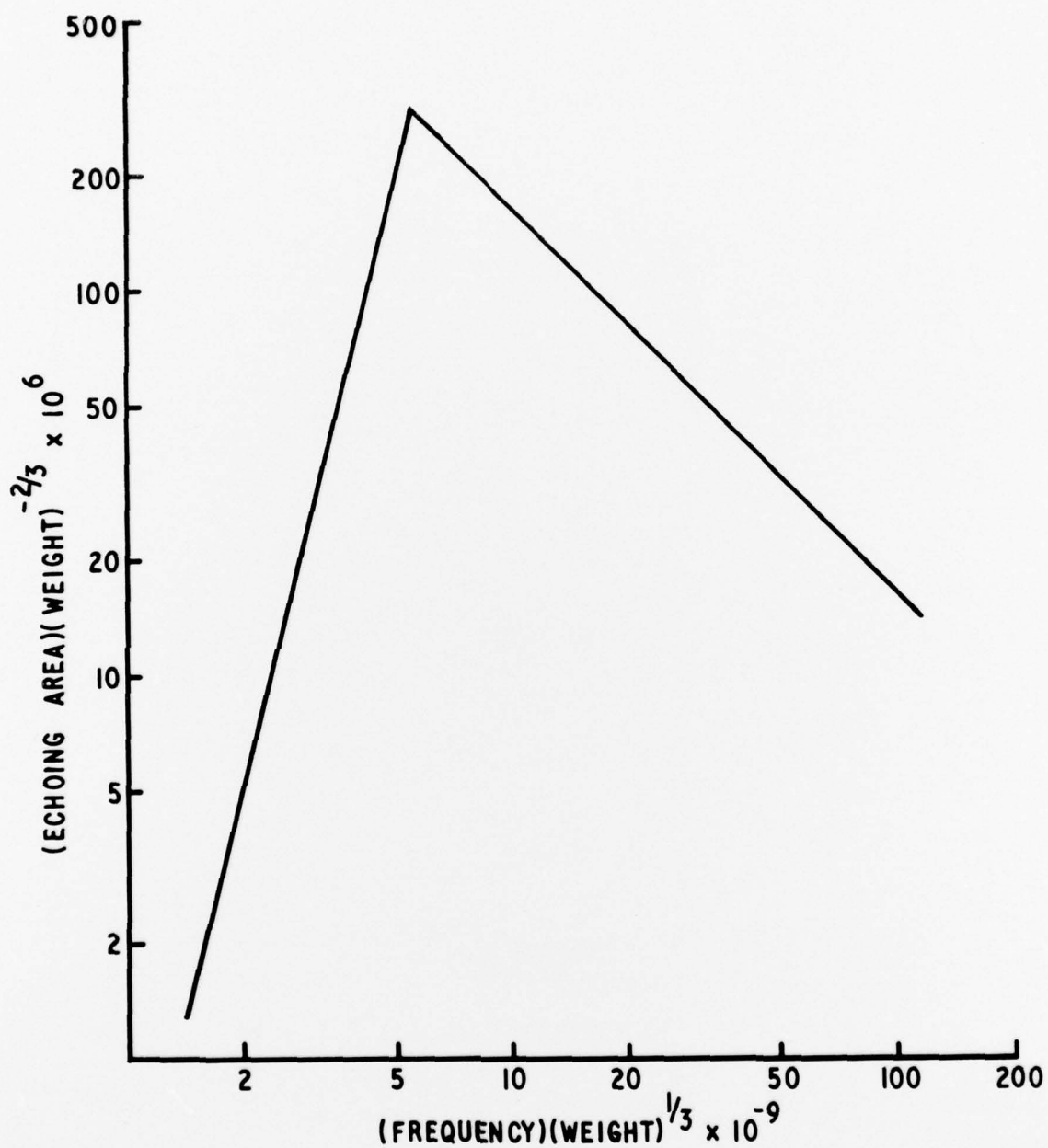RATE.

LINEAR POLARISATION

RR/R 31/9974

FIG. 8.

NORMALISED ECHOING AREA OF A SINGLE BIRD.

ECHOING AREA IN m² WEIGHT IN GRAMS FREQUENCY IN Hz.

1. ECHOING AREA EXCEEDED WITH PROBABILITY = 0·5
2. ECHOING AREA EXCEEDED WITH PROBABILITY = 0·1
3 ECHOING AREA EXCEEDED WITH PROBABILITY = 0·01
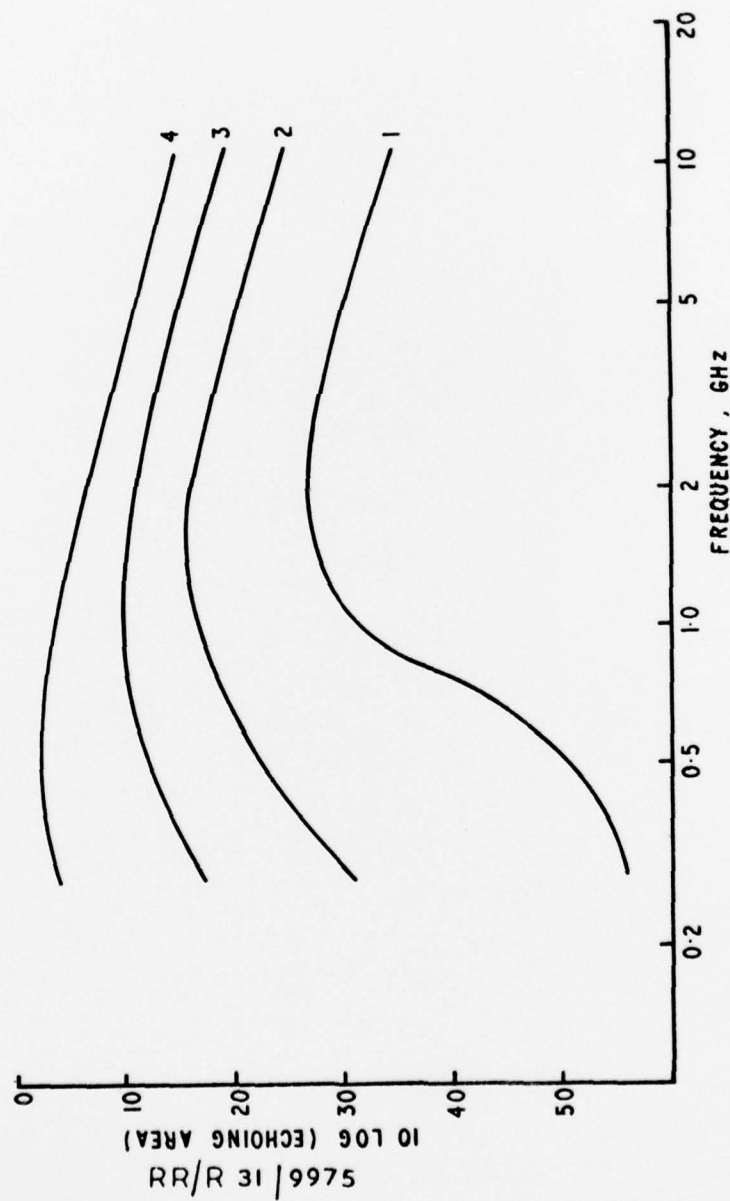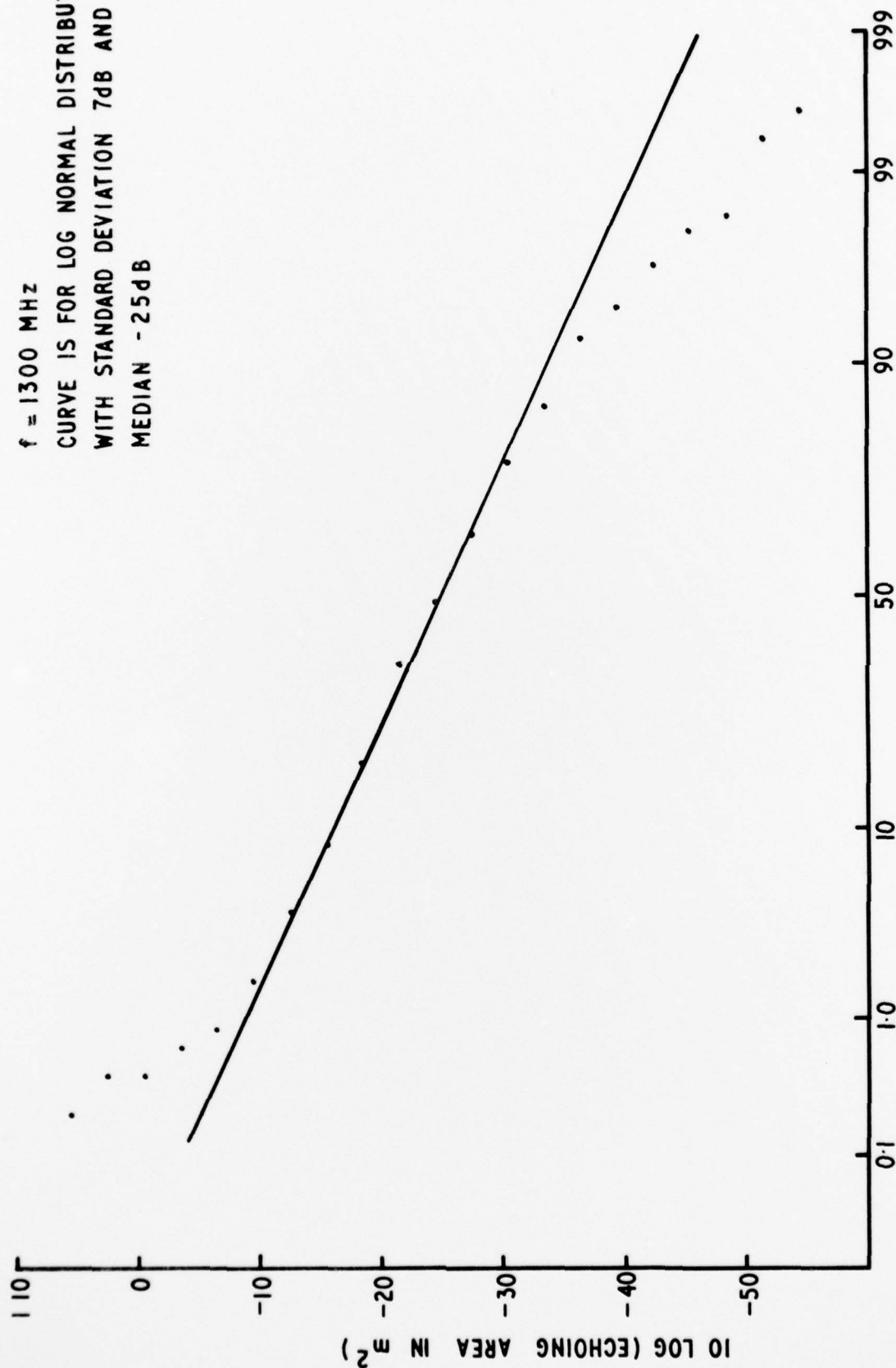4 ECHOING AREA EXCEEDED WITH PROBABILITY = 0·001

FIG. 9.

ECHOING AREA OF BIRDS, ASSUMING A TYPICAL MIXED
POPULATION.

RR/R 31/9975

f = 1300 MHz
CURVE IS FOR LOG NORMAL DISTRIBUTION
WITH STANDARD DEVIATION 7dB AND
MEDIAN -25dB

FIG. 10

ECHOING AREA OF BIRDS.

PERCENTAGE PROBABILITY THAT ORDINATE IS EXCEEDED

10 LOG (ECHOING AREA IN m^2)

WAVE HEIGHT H = 3m
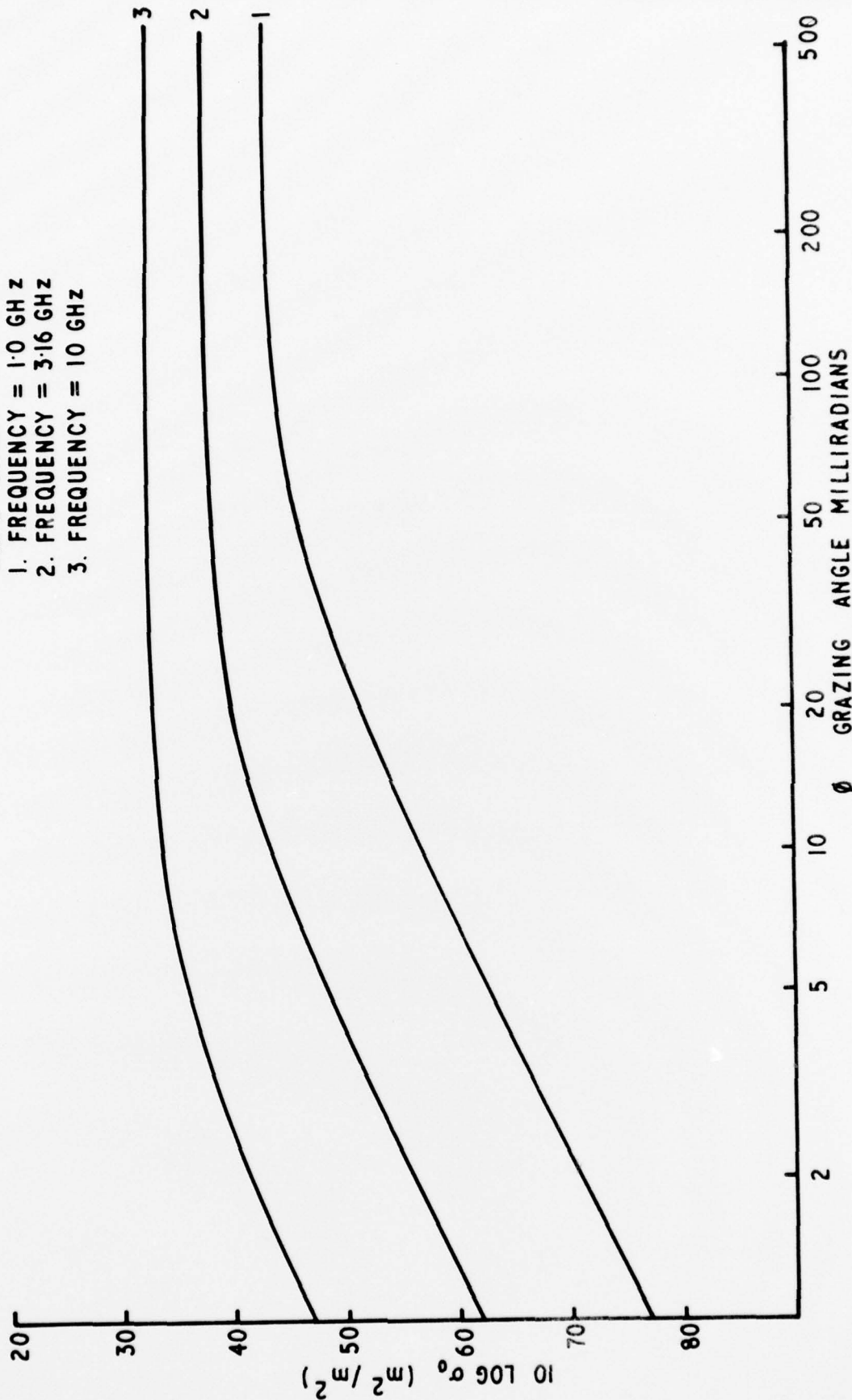1. FREQUENCY = 1·0 GHz
2. FREQUENCY = 3·16 GHz
3. FREQUENCY = 10 GHz

SURFACE REFLECTIVITY (σ_0) OF THE SEA.
HORIZONTAL POLARISATION

FIG. II

$\emptyset$ GRAZING ANGLE MILLIRADIANS

$10 \text{ LOG } \sigma_0$ (m^2/m^2)

WAVE HEIGHT = 3m
1. FREQUENCY = 1·0 GHz
2. FREQUENCY = 3·16 GHz
3. FREQUENCY = 10 GHz

FIG. 12

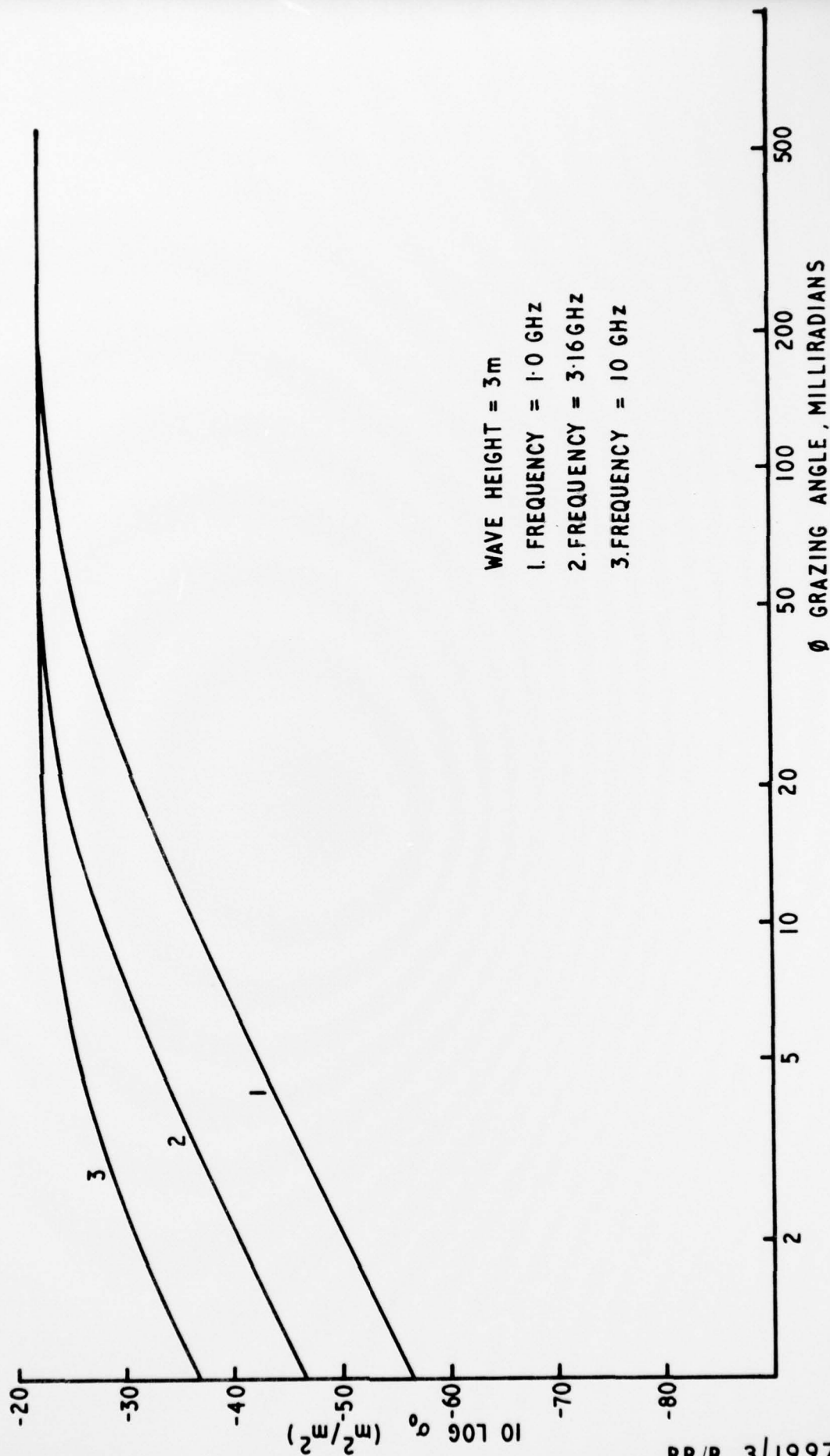SURFACE REFLECTIVITY (σ_0) OF THE SEA.
VERTICAL POLARISATION

$\emptyset$ GRAZING ANGLE, MILLIRADIANS

$10 \log \sigma_0$ (m^2/m^2)

RR/R 3/19972

DOCUMENT CONTROL SHEET

Overall security classification of sheet .....Unclassified... ....

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the box concerned must be marked to indicate the classification eg (R) (C) or (S))

1. DRIC Reference (if known)	2. Originator's Reference RRE Tech Note 797	3. Agency Reference	4. Report Security Unclassified Classification
5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location RSRE Malvern		
5a. Sponsoring Agency's Code (if known)	6a. Sponsoring Agency (Contract Authority) Name and Location		

7. Title
CONSIDERATIONS AFFECTING THE CHOICE OF FREQUENCY FOR SURVEILLANCE RADARS

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers)   Title, place and date of conference

8. Author 1 Surname, initials DODSWORTH E J	9(a) Author 2	9(b) Authors 3,4...	10. Date May 1976	pp. ref. 14
11. Contract Number	12. Period	13. Project	14. Other Reference	

15. Distribution statement
DSLR

Descriptors (or keywords)

SURVEILLANCE RADAR : CLUTTER : ECM

continue on separate piece of paper

Abstract Range performance in the clear, when no clutter or ECM is present, is largely independent of frequency if the aperture size of the receive aerial is held constant although there is a small but steady fall in performance as the frequency is raised because of increasing receiver noise factor and atmospheric attenaution. If the beamwidth rather than the aperture size is held constant the performance falls sharply as the frequency increases.

Clutter from the ground, the sea and from rain becomes more severe as the frequency increases. Clutter from birds is less severe at high frequencies.

With constant percentage bandwidth performance in noise jamming improves as the frequency is raised but a low frequency is to be preferred for chaff.